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Agricultural susceptibility to monsoon variability: A district level analysis of Maharashtra, India

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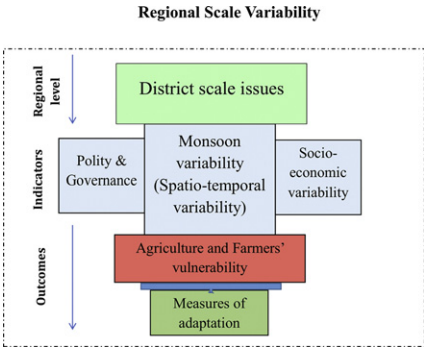
HIGHLIGHTS

- Inter-regional heterogeneity in monsoon variability and its impacts were investigated at district level in Maharashtra.
- We demonstrate the need for separate district-level plans for action on climate change.
- Information regarding the cropping pattern for the districts showing highest monsoon variability has been provided.
- Districts were ranked to help the government in specifying the expenditure in different sectors.
- District-scale adaptation measures to help formulate better policies for farmers.

GRAPHICAL ABSTRACT



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ABSTRACT

Indian Summer Monsoon (ISM) variability has always been a feature affecting Indian agriculture. However, nature of this variability is varying in the backdrop of climate change, and as a consequence, agriculture is getting significantly affected and subsequently threatening food security. To address the climate variability, most of the studies conducted so far have focused on a coarse scale such as Central India or Western Ghats. However, finer scale analysis for identification and quantification of the link between agriculture vulnerability and climate variables has not yet been attempted in a comprehensive manner. The latter is essential, as considering state and national domain as a single entity for regional level policy formulations have led to under-representation of grievances and issue related to agriculture and farmers in the past. In order to address these issues, focus of the current study is on finer scale analysis of districts of Maharashtra state in Western India. Inter and intra-regional spatio-temporal heterogeneity in monsoon variability parameters was found across districts of Maharashtra. Here, we ranked the districts of Maharashtra using monsoon variability index which includes six different monsoon variability parameters (Wet/Dry Spells, frequency/intensity of extreme rainfall events, deviation from the long-period average and daily-scale variability) by using factor analysis. Monsoon variability index indicated that districts under Vidarbha and Marathwada regions are at highest risk and need immediate attention from decision-makers and scientists. This index was further linked to average yield and cropped area using Structural equation modeling that will help to determine the ideal cropping pattern for the most vulnerable districts. An empirical model of monsoon variability is also proposed at district level for the state of Maharashtra that can contribute to the currently operating 'State Action Plan on Climate Change (SAPCC)' or can be used to formulate a new action plan at district level i.e. 'District Action Plan on Climate Change (DAPCC)'. The current study differs from other studies in terms of its application, levels of spatial aggregation and areas of coverage. The findings

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can be utilized by farmers and policy makers while formulating agricultural policies, risk reduction measures, and adaptation mechanisms to address the adverse impacts of climate change.

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1. Introduction

Climate variability has adverse impacts on crop production, and inadequate research carried out to assess the impacts of climate variability on crop production has aggravated the farmers' adaptive capacity (Jones et al., 2000). Due to climate variability, vulnerability of socio-economic factors increases, manifesting in sectors such as fishing, infrastructure, development and planning, and international trade (Kripalani et al., 2003; Ramesh and Goswami, 2007; Sivakumar et al., 2005). De et al. (2005) observed impacts of extreme weather events over Indian agriculture, economy and reported a monetary loss of $50–100 billion along with approximated casualties of 2.5 lakh lives across the globe. Areas with advanced agricultural technologies and higher yield were also found to be impacted significantly due to climate variability (Kang et al., 2009).

1.1. Link between climate variability and agriculture

In the Indian context, climate variability has caused a reduction in yield of sugarcane in Maharashtra by 30% and rice by 12% in Orissa (World Bank Report on Climate Change, 2008) along with significant reduction in dry land crops in Andhra Pradesh (Hiremath and Shiyani, 2013). Semi-arid region of Indian Peninsula has also faced a crisis in agriculture production due to climate variability (Gadgil et al., 2002). Productivity of Sorghum in Central and South-Central zones of India is comparatively lower than USA and China, mainly due to monsoon and temperature variability (Srivastava et al., 2009). The Western Ghats and coastal districts of North-Eastern region are also facing fluctuations in rice, sorghum, and maize due to climate change (Kumar et al., 2011). These studies indicate towards a link between climate variability and agriculture productivity, and thus a better understanding of climate variability is required to enhance agriculture yield along with farmers' adaptive capacity.

Climate variability is usually quantified in terms of factors such as temperature and precipitation (Srivastava et al., 2009). Out of these, the Indian summer monsoon (ISM) plays an important role in crop production as approximately 80% of Indian agriculture depends upon ISM and any variability in ISM leads to uncertainty in crop production (Gadgil et al., 2002; Ghosh et al., 2009; Singh et al., 2016; Sivakumar et al., 2005). Singh et al. (2014) identified an increase in frequency and intensity of dry spells (DS)/wet spells (WS) respectively over Indian sub-continent which further led to increasing agricultural, water-resource and infrastructural vulnerability.

1.2. Monsoon variability parameters

ISM variability is studied in terms of monsoon variability parameters such as WS/DS (Barron et al., 2003; Dash et al., 2009; Fox et al., 2000; Rockström et al., 2010; Sharma et al., 2010; Singh et al., 2014; Singh and Ranade, 2009; Sivakumar, 1992), extreme rainfall events such as frequency and intensity of rainfall extremes (Changnon et al., 1996; Dash et al., 2009; Ghosh et al., 2009; Singh and Sontakke, 2002; Sivakumar et al., 2005), deviation from long period mean (DLPA) and daily-scale variability (DSV). Singh and Ranade (2009) reported that over North-Western India, the intensity of rainfall during extreme events (WS/DS) is decreasing. In various studies conducted over India, it was observed that decrease in long wet events and prolonged dry spells resulted in shorter monsoon period from 1951 to 2013 (Dash et al., 2009; Ramesh and Goswami, 2007). Ghosh et al. (2009) through the analysis at finer resolution observed increasing trend for rainfall at some locations in Central India while no trend was being identified at other places. ISM also showed large spatio-temporal variation over arid and semi-arid regions of India (Dash et al., 2009; Sivakumar et al., 2005). Daily variability in rainfall is found to be increasing along with increase in frequency and magnitude of extreme rainfall events (Ghosh et al., 2009). The trend in different parameters of monsoon variability is varying at a larger extent post 1976/77. A major reason for the deviation in trend after 1976/77 is the regime shift experienced by tropical Pacific sea surface temperature (SST) during 1976/77 that led to significant changes in moisture flux, specific humidity and wind velocity (Sahana et al., 2015). Other factors that played a role in the observed change in trends after 1976/77 were rapid urbanization, deforestation, and industrialization (Ghosh et al., 2009). Contrasting results reported over different regions in regard to WS/DS, frequency/intensity of extreme rainfall highlight the existence of large spatio-temporal variability of rainfall across India and warrants region-specific study of monsoon variability.

1.3. State action plan on climate change and its limitations

So far, issues related to climate change and agriculture have been addressed at a larger domain such as Central India (Ghosh et al., 2009), Peninsular region (Krishnamurthy and Shukla, 2000) and country as a whole (Dash et al., 2009). Considering the state and larger domain as a single unit for addressing problems and policy formulations may lead to under-representation of regional problems (Dubash et al., 2014; SANDRP, 2014). For example, implementation of State Action Plan on Climate change (SAPCC) failed drastically due to lack of adequate information on regional level climate variability (Sikkim Climate Plan; Orissa Climate Plan). On the contrary, when the states included local knowledge in their plans, it led to improvements in performance of targeted plans e.g. Orissa Climate Plan focused on reducing transmission and distribution losses in privatized electricity sector via information collected from local stakeholders led to better energy distribution within the state; which was earlier unnoticed in National Action Plan on Climate change (Dubash et al., 2014). In India, Climate and agriculture-based policies are formulated for the entire state however, the crop productivity varies at micro level; thereby, having agricultural based policies at the macro level will not be able to provide solutions for micro-scale issues. This necessitates separate policy formulations related to climate variability at micro-level to devise structured mitigation/adaptation strategies. Further, from a policy formulation point of view, a different policy and adaptive measures are needed for regions exhibiting large spatio-temporal monsoon variability.

1.4. Regional level climate impacts

Our study specifically addresses district-level (regional) issues for Maharashtra State, India. India has been divided administratively into 29 different States and further sub-divided into districts. District is the basic administrative and decision-making unit in India to address climate change and agricultural issues. Significant climate variability exists at larger domain such as state and national level (Dash et al., 2009; Ranade and Singh, 2014) which is supposed to increase when the study is conducted at finer scale i.e. district level. Multiple regional models (Lal et al., 1999; Parry et al., 1999; Saseendran et al., 2000) are used to investigate the impacts of climate variability on agriculture as regional level strategies and plans are more useful for addressing

regional level climate impacts. The choice of the factors for monsoon variability was on the basis of their effect on agriculture and farmers' vulnerability. So far, the spatio-temporal variability of these monsoon variables at the regional scale is not addressed in policy formulation related to climate change for Indian states.

Therefore, by analyzing the problems at the district level for one of the most-agriculturally vulnerable state Maharashtra, we provided a framework to analyze monsoon variability, agriculture vulnerability and suitable adaptation measures at district-scale for Maharashtra. This framework can be adopted by any administrative unit across the world.

1.5. Objectives of the present study are

(i) To study the spatial and temporal variability of ISM at district level comprising trend-analysis of inter-annual rainfall variability, wet/dry spells, and extreme rainfall phenomenon pre-and post-1976/77.
(ii) To formulate a monsoon variability index by integrating all the parameters using Factor analysis (FA).
(iii) To rank districts based on Monsoon variability index and compare the results with the districts declared as drought-prone by Government of Maharashtra.
(iv) To establish the relationship between crop yield, cropped area, and districts displaying highest monsoon variability using Structural equation modeling (SEM).

The current study is divided into 2 parts: The first part of the study deals with the regional variation in monsoon variability at district scale and suggests the need for separate formulation of district action plan on climate change. The second part of the study establishes the relationship of districts exhibiting high monsoon variability with cropped area and productivity of major crops in those districts. It will aid in farmers' decision making regarding the type of crops that they should grow in different regions.

Structure of the paper is as follows: The first section is Introduction; then "Data and methodology" sections describe the study region, data sources, definition, and quantification of monsoon variables, followed by SEM results. Following section of the paper presents the "Results and discussion", and lastly "Implications of study" and "Conclusions".

2. Study region

The region chosen for the study (Fig. 1a) was state of Maharashtra (India), as 61% area of Maharashtra is semi-arid and is also part of semi-arid zones of India which exhibit large variability of rainfall, significantly affecting food production (Barron et al., 2003; Wani et al., 2009). Maharashtra is also one of the most agriculturally and socio-economically vulnerable states in India as every year a large number of farmers commit suicide due to climate-related stressors such as droughts, hail storms, and monsoon variability (Basu et al., 2016). The longitudinal and latitudinal expansion of Maharashtra is between 72°E to 83°E and 15°N to 23°N respectively. Further, Maharashtra has been divided into 6 regions which are Konkan coastal region in the west, between the Western Ghats and Arabian Sea; Marathwada (Aurangabad region) in the South-East; Vidarbha (Amravati and Nagpur division) towards the eastern side, Nashik in North-West; and Pune towards West-Central region of Maharashtra (Fig. 1a). Abbreviation of name of districts (shown in Fig. 1a) is mentioned in the Table 1.

Monsoon season in Maharashtra spans around 122 days from June to September. There is large heterogeneity in rainfall distribution pattern across Maharashtra. For example, Central Maharashtra receives rainfall around 500 mm, while coastal districts i.e. Konkan region receives around 6000 mm of rainfall and 2500 mm rainfall received in plain area, which shows the wide variability in the amount of rainfall received in the state. On an average, the number of rainy days is 75–85 in Konkan, 30–40 in Central Maharashtra, and 40–50 in Vidarbha region. State experiences high variability in annual rainfall with 31% in Marathwada, 30% in Central Maharashtra, 26% in Vidarbha, and 23% in Konkan region (NIDM, 2013).

3. Data and methodology

3.1. Data availability

Daily gridded rainfall data for the period of 1951–2013 at 0.25° × 0.25° were obtained from IMD which collects data from 2686 rain-gauge stations spread irregularly across India (IMD Pune, 2017). A number of rain-gauge stations in our study region i.e. Maharashtra is 278 and are unevenly distributed. Location of stations in Maharashtra is shown in Fig. 1b. These stations have a minimum data availability of 70% and the data were subjected to quality control such as removal of outliers and biases. Afterward, data were interpolated by Rajeevan et al. (2006) using Shepard interpolation method (Shepard, 1968) to regrid the data at a regular grid of 0.25° × 0.25°. Shepard (1968) used inverse distance weighing interpolation (IDW) method. In this method, the interpolated value is the weighted average of the neighboring observations. Here weights are assigned to the neighboring observed values based on their distance to the interpolation location. The method also considers temporal inhomogeneity in the dataset. This rainfall dataset has been used widely to study Indian Monsoon (Ghosh et al., 2009; Krishnamurthy et al., 2009; Singh et al., 2014).

The present work considered years from 1951 to 2013, as majority of the changes in climate appeared during this time period (Ramesh and Goswami, 2007). Further, the whole period was split into two regimes pre and post 1977, as the study by Sahana et al. (2015); Singh et al. (2014) showed that monsoon variability is increasing at a different rate after 1977. Data for crop productivity were acquired ("International Crop Research Institute for Semi-Arid Tropics,", 2013) from 1966 to 2009 for each district of Maharashtra state, India.

3.2. Methodology

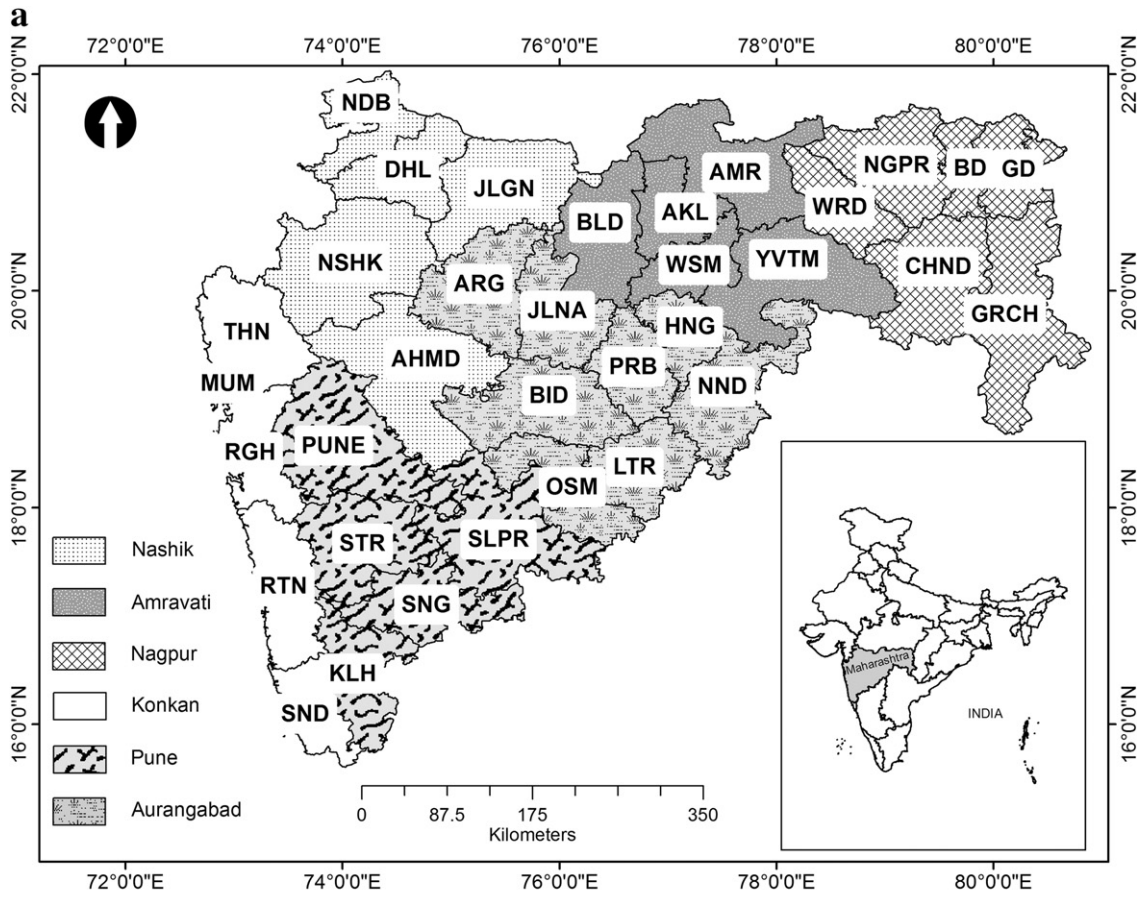
All the districts of Maharashtra were divided into grid boxes by casting on a fine mesh of 0.25° × 0.25° grid. The fishnet formed was used to extract the latitudinal and longitudinal extent of each district at 0.25° × 0.25° resolution. Daily rainfall data were extracted grid-wise for each district from 1951 to 2013 i.e. for 62 years. All the parameters of rainfall variability were analyzed for the four principal monsoon months i.e. June, July, August, and September (JJAS). Monsoon variability parameters studied during the study were WS/DS, extreme weather events, in particular frequency and intensity of extreme rainfall events, deviation of rainfall from long-period average (DLPA), and daily-scale variability (DSV) at the district level. The analysis was performed for each district individually from 1951 to 2013. Details of each parameter are described in following sub-sections.

3.2.1. Deviation from long-period average (X_{DLPA})

For each district, daily monsoon rainfall for JJAS months was averaged across years, which was subtracted from long-period average (LPA) of 62 years to calculate the deviation of rainfall from LPA, as shown in Eqs. (1)–(3);

$$\overline{X}.y = \sum_{d=1}^{D} Xdy/D \tag{1}$$

$$\overline{X}.. = \sum_{y=1}^{Y} \overline{X}_{.y}/Y \tag{2}$$



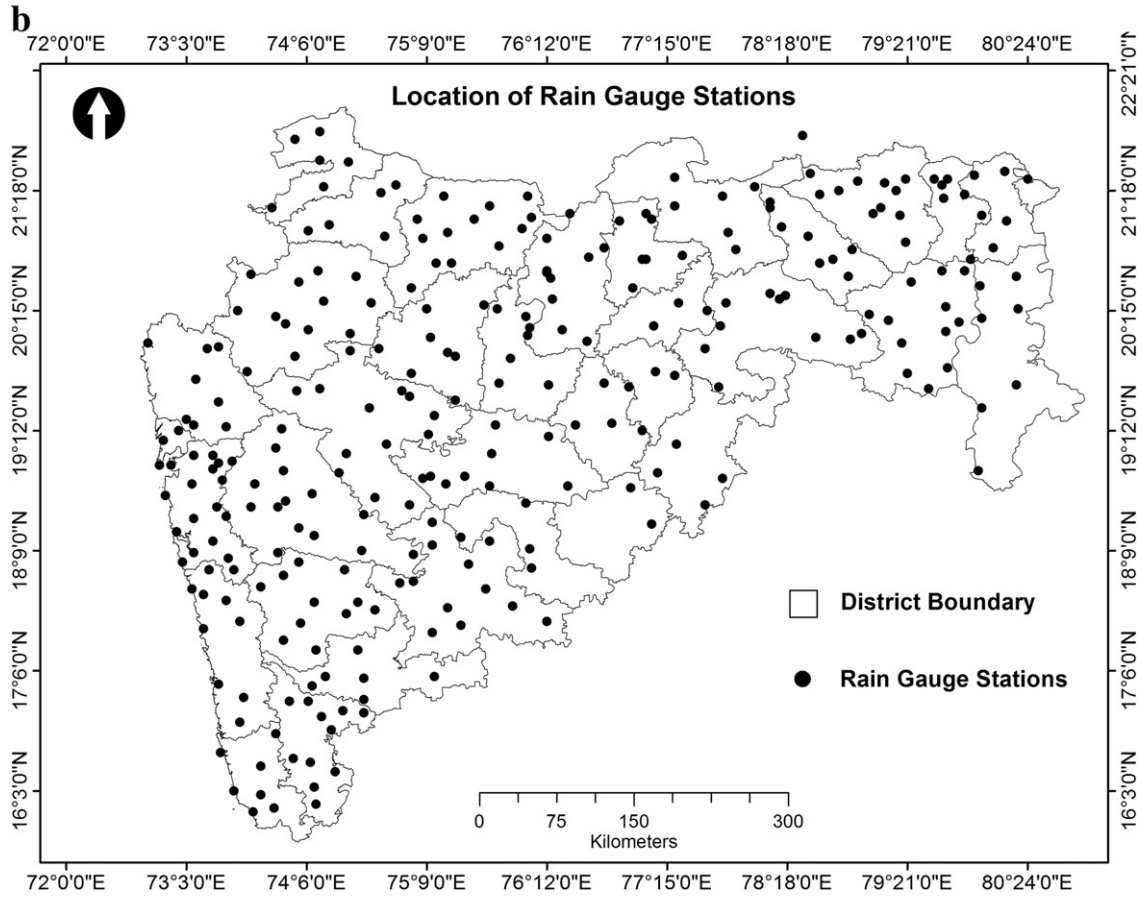


Fig. 1. a. Study region. b. Location of rain-gauge stations in Maharashtra.

Table 1
Abbreviation of district name.

Short name	District	Short name	District	Short name	District	Short name	District
AHMD	Ahmednagar	GRCH	Garhchiroli	NND	Nanded	STR	Satara
AKL	Akola	GNDY	Gondiya	NDB	Nandurbar	SNDR	Sindhudurg
AMR	Amravati	MUM	Greater Bombay	NSHK	Nashik	SLPR	Solapur
ARG	Aurangabad	HNGL	Hingoli	OSM	Osmanabad	THN	Thane
BND	Bhandara	JLGN	Jalgaon	PRB	Parbhani	WRDH	Wardha
BID	Bid	JLNA	Jalna	PUNE	Pune	WSHM	Washim
BLDN	Buldana	KLH	Kolhapur	RGH	Raigarh	YVTM	Yavatmal
CHND	Chandrapur	LTR	Latur	RTN	Ratnagiri		
DHL	Dhule	NGPR	Nagpur	SNG	Sangli		

$$XDLPA = \overline{X}.y - \overline{X}.. \quad (3)$$

where,
d = day.
D = total number of days
y = year
Y = total no of years.
X_{dy} = daily summer monsoon rainfall for each district.
$\overline{X}.y$ = average daily rainfall for each year.
$\overline{X}..$ = average rainfall for 62 years (LPA).
XDLPA = deviation of rainfall of each year from LPA.

3.2.2. Daily-scale variability ($\sigma_.$)

Variability discussed here was the daily variability of rainfall for JJAS. Change in seasonal variability across 62 years was calculated as shown in Eq. (4);

$$\sigma.y = \sum_{d=1}^{D} \left(\overline{X}.y - \overline{X}\ ..\right)^2/(D-1) \quad (4)$$

where,
σ_y = variability each year.
All other notations are mentioned in the calculation of Deviation from Long-Period Average (X_{DLPA}), in Eqs. (1)–(3).

3.2.3. Wet spells (WS)/dry spells (DS)

Extreme conditions of WS/DS are generally referred as active/break spells (Singh et al., 2014) and has been defined in different ways. Blandford (1886) was the first one to explain about break days. After him, the concept of break days has been explained in different ways by scientists such as (Alexander et al., 1978; Dash et al., 2009; Gadgil and Asha, 1992; Krishnamurti and Bhalme, 1976; Krishnan et al., 2000; Raghavan, 1973; Sikka and Gadgil, 1980; Yasunari, 1979), a summary of which is listed in Table 2.

WS/DS have been defined using outgoing long-wave radiation, wind speed, and pressure etc. During the present work, definition of WS/DS was adopted from Rajeevan et al., 2010; and Singh et al., 2014. To the best of our knowledge, the definition for active/break spells (WS/DS) has been applied at the district level for the first time.

Normalized daily rainfall time series (R) was obtained using Eqs. (3) and (4). If the value of R was >1 (less than −1) for at least three consecutive days then it was termed as wet (dry) spell (Eq. (5)).

$$R = \begin{cases} 1, \text{wet spell} \\ -1, \text{dry spell} \end{cases}, \text{for at least 3 consecutive days,} \quad (5)$$

where $R := \frac{X_{DLPA}}{\sigma_{.y}}$

The notations for symbols are mentioned in the calculation for DLPA and DSV in Eqs. (1)–(4).

3.2.4. Extreme rainfall events (frequency/intensity of extreme rainfall events)

Extreme rainfall events have also been described in different ways (Dash et al., 2009; Ghosh et al., 2009; Goswami et al., 2006; Krishnamurthy et al., 2009), a summary of which is listed in Table 3.

Analysis of extreme rainfall events was based on the study carried out by Ghosh et al. (2009); Krishnamurthy et al. (2009). In contrast to previously mentioned studies, the current study considers region specific threshold values for defining an event as extreme rainfall event.

For a given district, the frequency of extreme rainfall events for every year was calculated by identifying the number of days having rainfall greater than the threshold (90th percentile of rainfall across years), (Eq. (6)).

$$fyj = \sum_{d=1}^{D} (F(Pdyj > Pj)) \quad (6)$$

where,
j = number of districts in Maharashtra
d = day
D = total number of days
f_{yj} = frequency of rainfall for year y at district j

Table 2
Definition of active/break spells (wet/dry spells) by various researchers.

Author	Definition of wet/dry spells
Ramamurthy, 1969	Break/Active days: When the monsoon trough of low pressure is over foothills of Himalaya with weak or no rainfall over central India and high rainfall at Northern India.
Webster et al., 1998	Active/Break days: weak/strong spells of convection and 850 hPa zonal winds on region extending from 65 to 95°E and 10–20 °N.
S. K. Dash et al., 2009	Short wet spells = Rainfall ≥ 2.5 mm/day for <4 consecutive days Long wet spells = Rainfall ≥ 2.5 mm/day for ≥4 consecutive days; Dry spells = Rainfall < 2.5 mm/day for ≥ 1 day; Prolonged dry spells = Rainfall < 2.5 mm/day for ≥ 4 days
Krishnan et al., 2000	Days with positive Outgoing long-wave Radiation (OLR) anomalies over northwest and central India, in case averaged OLR anomaly exceeds 10 W/m^2 at core monsoon zone are defined as "Break days"
Singh and Ranade, 2010	Wet: At least 25 mm rain in 7 days, with ≥1 mm on at-least 5 out of 7 days Dry: Duration between 2 subsequent wet spells
Singh et al., 2014	Precipitation normalized anomaly with one standard deviation more than daily precipitation for at least 3 consecutive days
Rajeevan et al., 2010	Active/Break: Rainfall normalized anomaly exceeding (+1) and (−1) for at least 3 consecutive days

Table 3
Definition of extreme rainfall events by different researchers.

Author	Definition of extreme rainfall events (frequency and intensity)		
Goswami et al., 2006; Rajeevan et al., 2008	5 mm/day ≤ Light/moderate rainfall < 100 mm/day	100 mm/day – Heavy rainfall < 150 mm/day	Very heavy rainfall ≥ 150 mm/day
Dash et al., 2009	Short rain spells = Rainfall ≥ 2.5 mm/day for <4 consecutive days	Long rain spells = Rainfall ≥ 2.5 mm/day for ≥4 consecutive days	Dry spells = Rainfall < 2.5 mm/day for ≥1 day; Prolonged dry spells = Rainfall < 2.5 mm/day for ≥4 days
Krishnamurthy et al., 2009	Rainfall events > threshold value (90th and 99th percentile)	–	–
Ghosh et al., 2009	Rainfall events > threshold value (25th, 75th, 95th, 99th percentile values)	–	–
Pattanaik and Rajeevan, 2010	Light rainfall = 0.0 < Rainfall ≤ 10.0 (mm/day) Moderate = 10.0 < Rainfall ≤ 35.5 (mm/day)	Heavy rainfall = 64.4 < Rainfall ≤ 124.4 (mm/day)	Very heavy rainfall = 124.4 < Rainfall ≤ 244.4 (mm/day)

P_{dyj} = rain on day d in year y at district j
$P_{j:}$ = rainfall threshold for district j
F = indicator function, whose value is 1 when true otherwise 0

Intensity was calculated by averaging the daily rainfall anomaly every year only for the days where rainfall exceeded the threshold value (Eq. (7)).

$$r_{yj} = \left(\frac{\sum_{d=1}^{D} F(Pdyj > Pj) \times P_{dyj}}{fyj} \right) \tag{7}$$

where,

r_{yj} = intensity of rainfall for year y at district j
F = indicator function, whose value is 1 when true otherwise 0

All other symbol notations are mentioned in the calculation for the frequency of extreme rainfall in Eq. (6).

3.2.5. Monsoon variability index using factor analysis

We cannot propose planning and development strategies by considering each parameter in isolation, thereby we should have a unified index that combines all parameters into a single parameter. In order to achieve this, we first identified heterogeneity of different regions within Maharashtra and then clustering of different regions was performed according to their monsoon variability pattern using Factor analysis (FA) (Anderson and Gerbing, 1988). In order to assess the impact of Monsoon variability manifested in terms of factors such as WS/DS, extreme rainfall events, DLPA, DSV etc., Monsoon variability index (*MVI*) was formulated based on factor analysis.

$$MVI = \Lambda_x X^T + \zeta \tag{8}$$

Here, $MVI \in R^{n\times 1}$ Y is Monsoon variability index, $\Lambda_x \in R^{n\times m}$ is factor loading and $\zeta \in R^{n\times 1}$ is the measurement error, n is number of years and m is number of factors. Given a set of measurements $X \in R^{n\times m}$ (comprised of the WS/DS, extreme rainfall events, DLPA and DSV), factor analysis allowed to estimate factor loadings Λ_x and factor score *MVI*. In $R^{n\times m}$, R is real-valued vector space and superscript "n" and "m" represents rows and columns respectively.

Using this index, districts were ranked from highest to lowest vulnerability (Eq. (8)). In our analysis for Structural equation modeling (SEM) and factor analysis, the results have been explained in terms of increase in monsoon variability. The impact assessment of monsoon variability on crops was performed from drought perspective. Here, drought conditions were referred to weakened rainfall conditions that were characterized by conditions such as decrease in frequency of extreme rainfall events, wet spells and DLPA, and increase in the intensity of extreme rainfall events, dry spells, and DSV.

Using year estimated factor score, the slope of *MVI* was calculated, where negative (positive) slope represents a decrease (increase) in Monsoon variability. Statistical significance of the calculated slope was performed at $\alpha = 0.1$. Using trend analysis of *MVI*, districts were ranked as highest to least vulnerable districts with regard to overall monsoon variability.

3.2.6. Structural equation modeling (SEM)

Most of the studies have used different crop models such as CERS for wheat and rice, maize, sorghum, pearl millet and barley; SOYGROW for Soybean, CROPGROW for bean and peanut to identify the relationship between productivity of these crops and climate variability (Lal et al., 1999; Parry et al., 1999; Saseendran et al., 2000). These crop models fail to quantify the effects of monsoon variables on crops when all crops were included in the model simultaneously. Along with this, these models are run for shorter time scale (seasonal scale) rendering them unsuitable for climate scale vulnerability assessment. However, our study established the relationship between productivity of major crops from 1966 to 2009 and different parameters of monsoon variability in the same time period using SEM (Bollen, 1989) which is used for the first time to establish such type of relationship.

The relationship between each parameter of *MV* and major crops was established using SEM, (Bollen, 2010). SEM has been used to segregate the overall effect into multiple indirect and direct effects. Indirect pathway has at least one mediating variable between cause and effect variables while the direct path has no mediating variable. Further, SEM allows estimation of latent variables (variables that are not directly measured but manifests as other measured exogenous and endogenous variables). Further details on SEM can be found in Bollen (1989).

The main advantage of the method used in our study is that it traces the impacts on crops by different monsoon variables and identifies the dominating factor contributing maximum towards the crop vulnerability of each district. Thereby, this process helps us to identify the type of crop needed to be grown according to the changing climate profile of each district that will help in improving the agricultural productivity of a particular district, and also in reducing the vulnerability of farmers.

3.2.7. Quantile distribution method

This method was applied to each parameter of monsoon variability separately. For example, we have applied quantile distribution method for the trend in WS and divided the same into 4 different classes, as shown in Fig. 3(a). Similarly, it was done for other monsoon variability parameters as well.

During the present work, quantile distribution method was applied to divide the different monsoon variability parameters into four groups. Here, the value of monsoon variables was arranged in ascending order, in which the middle value was the median, also known as 50th percentile or 2nd quartile and the limits were the minimum and maximum value of the dataset. The first quarter of this arranged dataset was 1st quartile or 25th percentile and 3rd quarter is 3rd quartile or 75th percentile. The maximum value was 100th percentile or 4th quartile. In this way, these four different quartile values were four equal classes in

which dataset of monsoon variability parameters was distributed, which were named as highly decreasing, decreasing, increasing, highly increasing in the paper (Fig. 3(a–f)). Further details on quantile can be found in Gilchrist (2000).

3.2.8. Trend analysis

The trend was determined by linearly regressing monsoon variability parameters upon time (1951–2013). Trend analysis for monsoon rainfall using linear regression used was followed by the study carried out by Ghosh et al. (2009).The statistical significance of trend was tested at $\alpha = 0.10$. For the sake of convenience, only significant results are shown in the paper.

4. Results and discussion

Variability in the trend of monsoon variables was observed for all the districts from 1951 to 2013 (63 years). The trend of WS/DS, intensity/frequency of extreme rainfall and daily–scale variability was found to be heterogeneous both spatially and temporally (depicted in Fig. 2(a)). All the figures for monsoon variability were shown with two slopes, pre and post 1976/77 to assess the behavioral shift in monsoon patterns for different districts after this time period. The climatological mean of all monsoon variability parameters for a period of 1951–2013 was used as a threshold to identify number of years for all six monsoon variability parameters above and below this threshold. Years with monsoon variability greater than the threshold are represented with blue color while lower than the threshold are represented in red-color (Fig. 2(b–g)). On the basis of the range of all the parameters (Fig. 2(a)), districts exhibiting highest, intermediate and least variability are represented spatially (Fig. 3(b–g)), with red color representing maximum value; blue representing minimum, white color representing non-significant value and other colors representing the intermediate value. Information regarding different regions of Maharashtra is shown in (Fig. 1a).

From Fig. 2(b–g), it can be seen that after 1976/77 continual increase in trend of dry spells, intensity of rainfall and deviation from long-period average; and decrease in trend of wet spells, frequency of extreme rainfall events and daily scale variability became more prominent. It is mainly due to regime shift experienced by tropical Pacific sea surface temperature (SST) during 1976/77 (Sahana et al., 2015) and changes in regional circulation pattern (Ramesh and Goswami, 2007). A significant shift in monsoon variability trend, pre-and post-1976/77, indicated changing monsoon pattern for districts of Maharashtra. Further, it has been reported in the literature that small change in latitude and longitude leads to significant changes in the location of a downward branch of regional Hadley circulation pattern, inhibiting regional convection and subsequently exerting significant impacts on regional rainfall (Ramesh and Goswami, 2007). Regional circulation pattern here refers to changes in monsoon variability due to regional factors such as topography, non-uniform population growth, urbanization, deforestation, land-use changes, global warming and greenhouse gas emissions (Ghosh et al., 2011, 2009). A significant shift in monsoon variability trend, pre-and post-1976/77, indicated changing monsoon pattern for districts of Maharashtra.

4.1. Wet/dry spells

4.1.1. Wet spells (WS)

Statistically significant declining trend of WS was observed across majority of the districts (16/34), but few districts (3/34) were also found to show statistically significant increase; among these, only districts with highest and lowest statistically significant trend, (range obtained from Fig. 2(a)), are shown in the (Fig. 2(b)). Numbers of wet spells were found to be highly increasing (Fig. 3(a)) for districts in Nashik and Konkan region, while highly decreasing (Fig. 3(a)) for Vidarbha region, indicating that Vidarbha is more sensitive to changing the climate. A few districts in Vidarbha region are showing decreasing trend in number of WS (slope < -0.03; Fig. 2(a)) such as Akola, Washim, Wardha (Fig. 3(a)) but Gondia, Yavatmal and Chandrapur (Fig. 3(a)) are showing increase in WS (slope > -0.02; Fig. 2(a)). Districts of Nashik and Konkan region are displaying a significant increase in the number of WS. Percentage of districts showing increasing/decreasing and statistically non-significant trend for number of wet spells is shown in (Fig. 4(a)).

Districts with the largest change in the number of wet spells after 1977 were Akola, Amravati, Washim, Greater Bombay, Nashik, and Ratnagiri, (SI-Table 1). These districts belong to Vidarbha and Konkan region of Maharashtra. Greater Bombay, Nashik, and Ratnagiri exhibited fluctuation after 1976/77; but lacked any significant increasing/decreasing long-term trend (1951–2013) for WS (Fig. 3(a)). Results showed that districts belonging to the same region exhibited variability in the frequency of wet spells and districts belonging to different regions showed similar behavior. This analysis carried out at finer resolution brought out the intra-regional heterogeneity and inter-regional homogeneity which was missing at coarse resolution analysis carried out in previous studies. Post-1976/77 period was also found to exhibit a significant change in the trend of WS for most, not for all the districts, which indicated that only a few districts were largely affected by the regime shift, urbanization, and industrialization, indicating towards more sensitivity and lesser adaptive capacity of such districts.

4.1.2. Dry spells (DS)

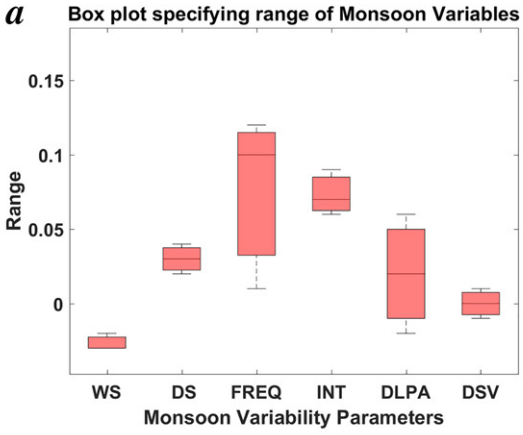
Dry spells were found to increase across all the districts of Maharashtra. Districts with highest and lowest trend magnitude (range obtained from Fig. 2(a)), are shown in the Fig. 2(c). Out of 34 districts, 12 districts showed a statistically significant increase and most of them belong to Vidarbha and Aurangabad region, Fig. 3(b). Amravati, Akola, Chandrapur, Hingoli, and Nanded of Vidarbha region were found to reflect the large variation in their behavior pre and post 1976/77, (SI-Table 1). The results indicated that dry spells were increasing at a higher rate (slope > 0.04; Fig. 2(a)) in Akola, Nanded and Chandrapur in comparison to the other districts (Fig. 3(b)). Like WS, intra-regional heterogeneity was also found to exist in districts for DS, further strengthening the argument, that monsoon variability patterns should not be generalized for the entire state or larger domain such as Central India or Peninsular India etc. Percentage of districts showing increasing/decreasing and statistically non-significant trend for number of DS is shown in Fig. 4(b).

In the current study, part of the study region overlaps with Central Indian region and thereby, we validated the results at district level with the studies over Central Indian region (Dash et al., 2009; Ghosh et al., 2009; Rajeevan et al., 2010; Singh et al., 2014). According to Dash et al. (2009), the number of WS decreased during the past half-century which is consistent with the results obtained in the present analysis and can be attributed to local convection, thunderstorm, and other intensified mesoscale conventions. The mean JJAS rainfall over districts was decreasing significantly, which is consistent with the results obtained over the core monsoon region by Singh et al. (2014) and over whole Indian subcontinent by Turner and Annamalai (2012). Our results for pre and post 1976/77, corroborates significantly with the results obtained by Singh et al. (2014) over Central India.

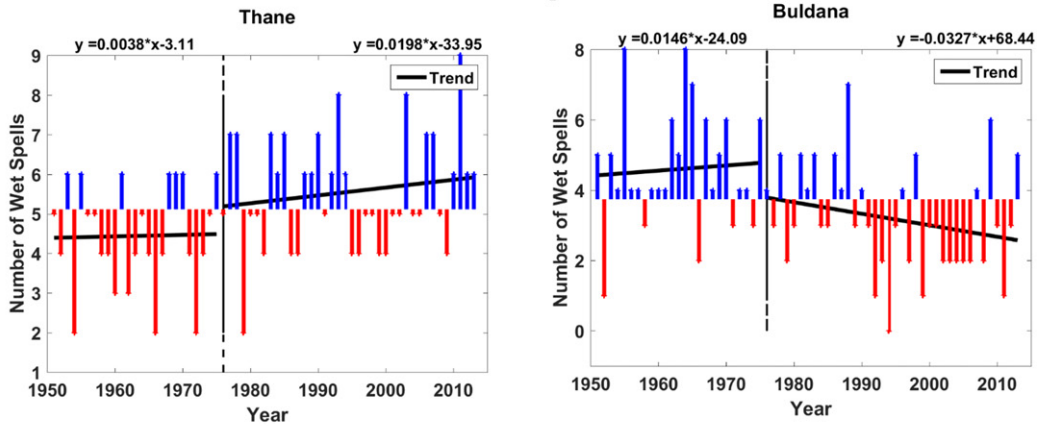
4.2. Extreme rainfall events

4.2.1. Frequency of extreme rainfall events

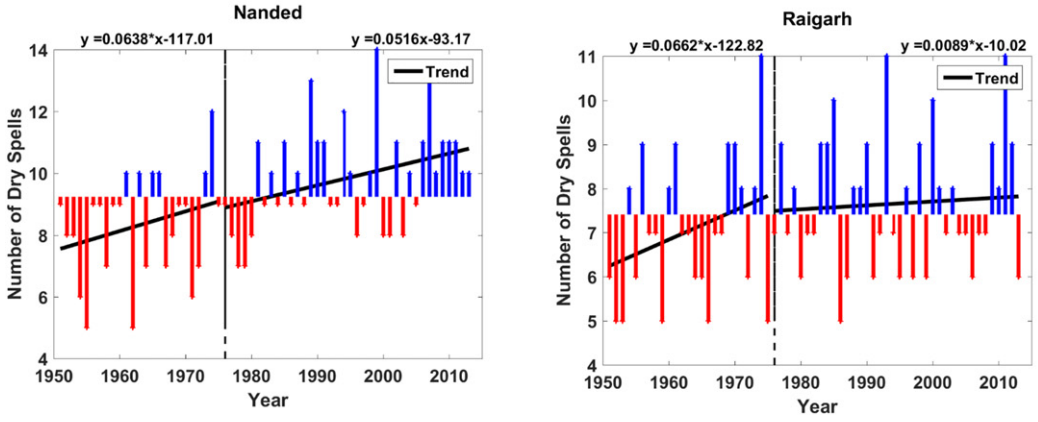
During the present study, 8/34 districts showed a significant decline in frequency and only districts with highest and lowest magnitude of a trend in frequency (range from Fig. 2(a)), is shown in Fig. 2(d). Pune, Satara and Ratnagiri showed increase (slope > 0.12; Fig. 2(a)) in frequency while districts of Marathwada and Vidarbha region exhibited decreasing trend (slope < 0.01; Fig. 2(a)) in frequency (Fig. 3(c)). In other districts, no fluctuation in trend was observed. Results displayed large inter and intra-regional spatio-temporal variability in the



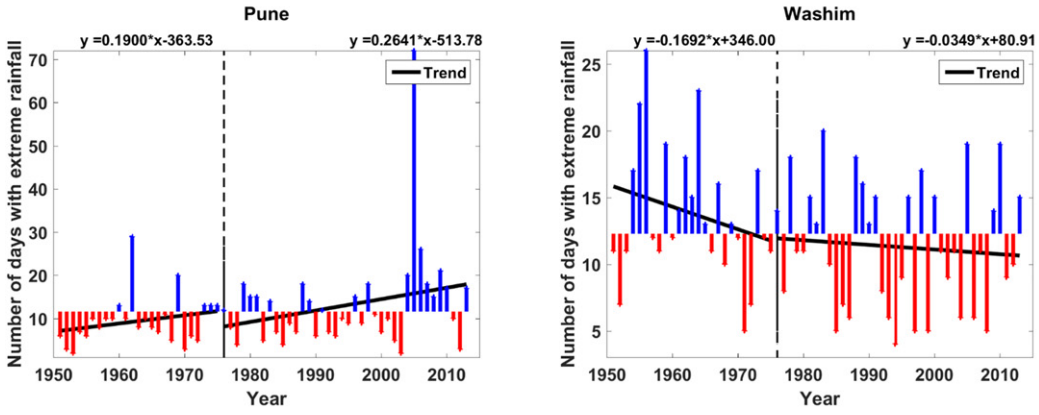
(b) Wet Spells



(c) Dry Spells



(d)Frequency of extreme rainfall events



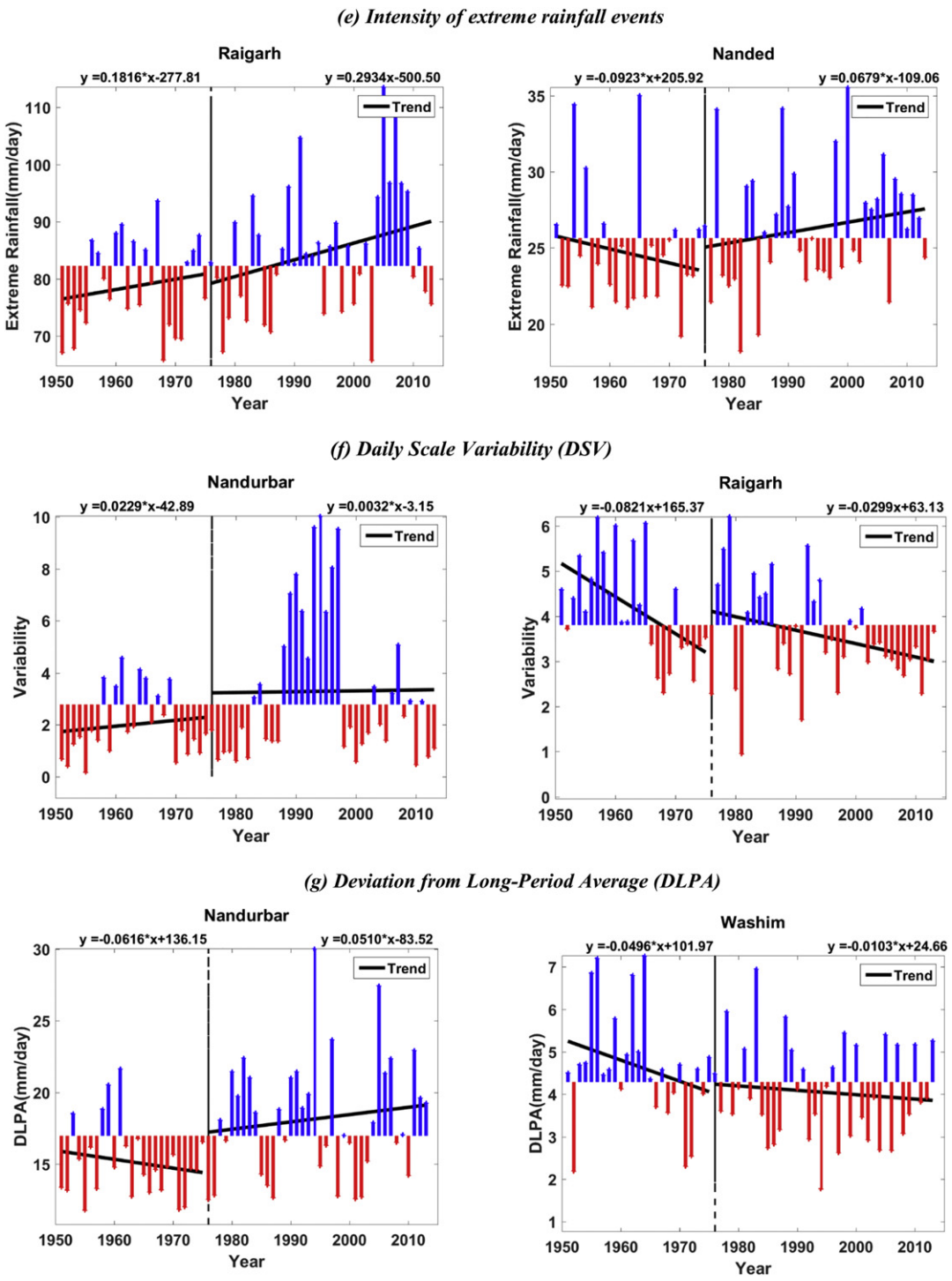


Fig. 2. Temporal Variability of all six Monsoon variability parameters across Maharashtra.(a) Box Plot specifying range of monsoon variables (Central box represents value from 25th to 75th percentile, the middle line is median, vertical lines extend from minimum to maximum value) (Coding for panel (a) - WS: Wet Spells, DS: Dry Spells, FREQ: Frequency of extreme rainfall events, INT: Intensity of extreme rainfall events, DLPA: Deviation from Long-Period Average; DSV: Daily Scale Variability).(b) Number of Wet spells (c) Number of Dry Spells (d) Frequency of extreme rainfall events (e) Intensity of extreme rainfall events (f) Daily-scale variability (g) Deviation from Long-Period Average (DLPA). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)[From Panels (b–g): X-axis represents year and Y-axis represents value of that particular variable; Red and Blue lines indicate years with values of monsoon variability parameter, less and greater than mean respectively; Dotted black line indicates the time period of 1977; solid black line represents trend line][Left Side Column: Largest increase; Right Side Column: Largest decrease of a particular variable]

frequency of rainfall across districts of Maharashtra. Variation in trend of frequency was found to be prominent after 1976/77 for Thane, Ratnagiri and Greater Bombay of Konkan region; Nagpur, Hingoli of Vidarbha and, Aurangabad and Parbhani of Marathwada regions (SI-Table 1) but these districts did not display statistically significant trend at $\alpha = 0.10$ from 1951 to 2013 (Fig. 3(c)). Percentage of districts showing increasing/decreasing and statistically non-significant trend for the frequency of extreme rainfall events is shown in Fig. 4(c).

4.2.2. Intensity of extreme rainfall events

Out of the 34 districts, 12 districts showed a significant change in intensity profile and districts with highest and lowest change (range from

Fig. 2(a)), are shown in the Fig. 2(e). Trend analysis indicated increase in intensity of rainfall with the time period for all the 12 districts. Out of these, the majority of them fall under Vidarbha region, as shown in Fig. 3(d). Gondiya and Bhandara (Vidarbha region), and Ratnagiri (Konkan region) displayed the largest increase (slope > 0.09; Fig. 2(a)) in intensity than Nagpur, Gadchiroli, and Nanded of Vidarbha region (slope < 0.06; Fig. 3(d)). After 1976/77, Latur, Wardha, Jalgaon, and Gondiya districts of Vidarbha and Marathwada regions displayed the highest variation (SI-Table 1) but lacked long-term statistically significant trend (Fig. 3(d)). Results indicated that Vidarbha and Marathwada regions displayed a significant change in rainfall intensity from past 30 years but Konkan and Nashik region were showing variability from the long time period (1951–2013). Similar to other parameters of monsoon variability, the intensity of extreme rainfall also showed intra and inter-regional heterogeneity and spatio-temporal variability for districts of Maharashtra. Percentage of districts showing increasing/decreasing and statistically non-significant trend for the intensity of extreme rainfall events is shown in Fig. 4(d).

From 1981 to 2011, study carried out by Singh et al. (2014) observed an increase in the intensity of heavy rainfall events and a decrease in frequency of extreme rainfall events, which is consistent with the results obtained in the present study at district-level, as we also found the increase in the intensity of rainfall events after 1976/77. This increasing trend could be attributed to anthropogenic aerosol forcing (Bollasina et al., 2011; Ramanathan et al., 2005) and large-scale monsoon variability over the multiple decades (Turner et al., 2005; Wang et al., 2013). Global warming might be the cause for the same, as it leads to increase in moisture content of the surroundings (Singh et al., 2014). Such high variability in frequency and intensity may also be attributed to sea surface temperature anomaly over tropical Indian Ocean (Rajeevan et al., 2008). According to Rajeevan et al. (2008), increase in temperature due to global warming leads to increased evaporative flux from the ocean, further leading to increased moisture content of the atmosphere subsequently resulting in extreme rainfall events. According to Trenberth et al. (2003), when these heavy rainfall events exceed evaporation rates then rainfall intensity increases in proportion to increase in moisture content. Increasing moisture content in the atmosphere increases the precipitation rate locally by stimulating storm and depressions by the release of latent heat and by supplying more moisture. The positive feedback of moisture leads to increase in intense and frequent rainfall events. Apart from these factors, post 1976/77, significant shift towards industrialization and urbanization led to more climate-related effects manifested in terms of change in frequency and intensity of extreme events (Ghosh et al., 2009; Singh et al., 2014). Our analysis corroborates the observed change in increased Monsoon variability after 1976/77 by Sahana et al. (2015); Shahid (2011); Singh et al. (2014).

4.3. Rainfall anomaly and daily-scale variability

Rainfall anomaly and daily-scale variability also showed large fluctuations in trend after 1976/77 like the other parameters of monsoon variability. Out of 34 districts, 11 districts showed significant trends for both DLPA and DSV, out of which 5 were showing statistically decreasing trend and 6 were showing a statistically increasing trend (Fig. 3(e–f)). Only districts with highest and lowest value of DLPA (highest: slope > 0.06; lowest: slope < −0.02; Fig. 2(a)) and DSV (highest: slope > 0.01; lowest: slope < −0.01; Fig. 2(a)) are shown in the Fig. 2(f–g).

The high magnitude of daily-scale variability was found in the districts of Nashik and Marathwada region, (Fig. 3(e)) while districts of Konkan and Nashik region displayed high deviation from long-period average (Fig. 3(f)). Our analysis showed that variability in rainfall anomaly and daily-scale variability was found to be more prominent in Konkan and Aurangabad region. Percentage of districts showing increasing/decreasing and statistically non-significant trend for DLPA and DSV are shown in Fig. 4(e–f) respectively.

The results of high CV next to the very low CV in Fig. 3(a–f) highlight the high inter-regional variability; which strengthens our arguments of the need for distinct district-wise policy for each district in Maharashtra, India. Observed regional heterogeneity in adjoining areas can be attributed to land-use changes, urbanization, deforestation, globalization etc. as pointed out by Ghosh et al. (2011). Results strongly bring out the gaps in planning where entire Maharashtra has been considered as a single region (unit) for analysis and policies have been formulated for the entire State.

4.4. Monsoon variability index

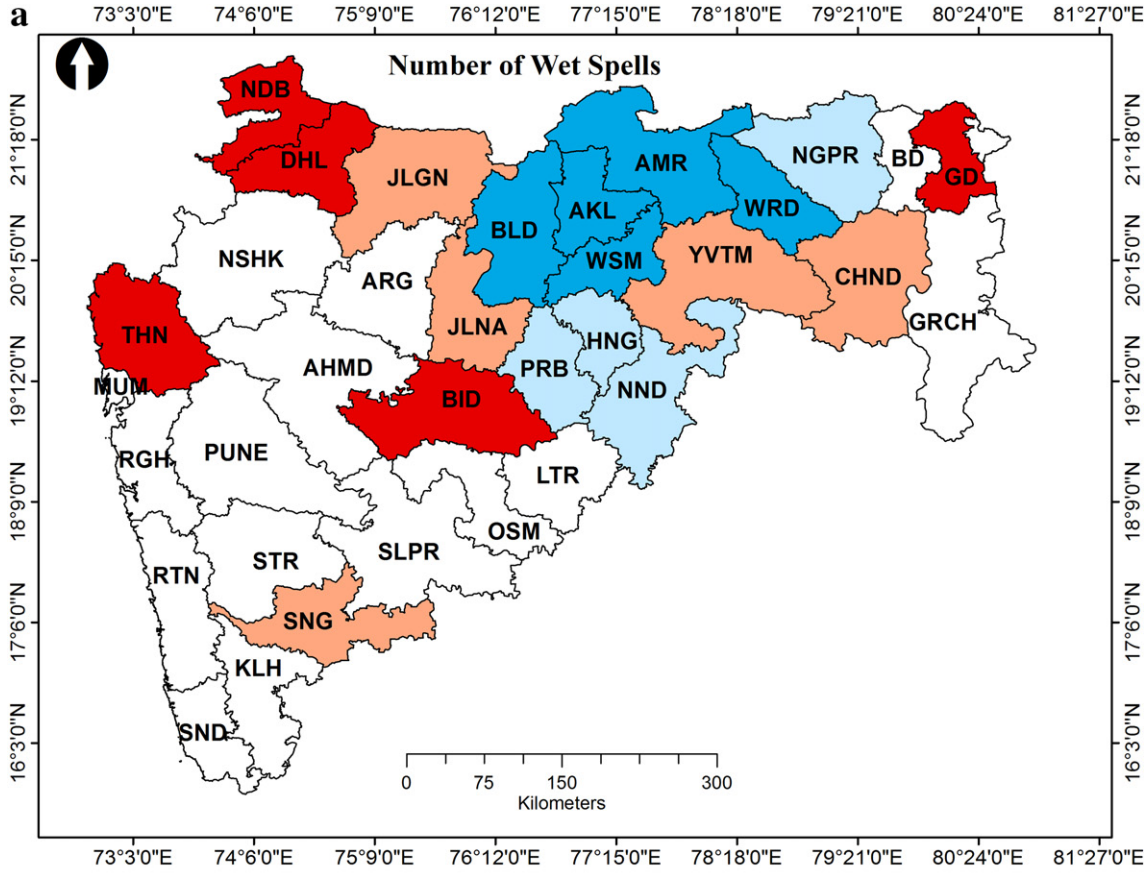
Till now, our study addressed separately for different parameters and explained results according to each parameter. In order to propose planning and development strategies for each district, a unified index was formed by combining all parameters of monsoon variability using Factor analysis (Anderson and Gerbing, 1988). The relationship between monsoon variability factors and *MVI* is depicted in Fig. 5a, where monsoon variables are represented by squares and *MVI* is represented by a circle. Single-headed arrows from endogenous to exogenous variables are the respective factor loadings or influence of that parameter on latent variable and double-headed arrow represents the covariance between parameters. Factor analysis helps in integrating all the parameters of monsoon variability and formulating one model to display the districts that are at highest and lowest risk due to climate change. Factor analysis in the current study will help in identifying hot spots in Maharashtra and these hot spots can be provided special attention during extreme climatic events.

Districts showing a significant increase in *MVI* are shown in Fig. 5b. Only 13 districts showed a significant increase in *MVI* from the period 1951–2013, out of which districts of Vidarbha and Aurangabad regions showed the largest increase in *MVI* (Fig. 5b). The findings of this study are partially consistent (13/34 districts) with districts declared as drought-prone by Government of Maharashtra (25/34 districts). Reasons for the observed variability in Fig. 5b are reported to be the same as for Fig. 3(a–f). This is because Fig. 5b was made by integrating all the monsoon variables parameters using factor analysis.

4.5. Districts under drought prone area declared by government of Maharashtra

Every year, Government of Maharashtra declares few districts under drought-prone area program (DPAP) based on the monsoon extremes and rainfall pattern. This is done to procure financial assistance from the central government for improving the situation of drought-affected districts. In the year 2015–16, Maharashtra government declared 25/34 districts i.e. 73% under DPAP (NRDWP, 2015-2016, Ministry of Drinking Water and Sanitation), which is a very high number when compared with the results obtained in this study. According to this study, 13/34 i.e. only 38% districts are showing an increase in drought and monsoon variability, out of which only 2 are facing the drastic situation as shown in the Fig. 5b. The comparison of districts declared under DPAP by Maharashtra government and the present study is shown in Fig. 5c. Further, the present study highlights the districts that exhibited large vulnerability and are highly drought-prone, yet not considered for assistance by the government.

Fig. 3. District level mapping of spatial variability for all the six monsoon variability parameters (Districts are ranked according to the quantile values for all parameters of monsoon variability): (a) Number of Wet spells (b) Number of Dry Spells (c) Frequency of extreme events (d) Intensity of extreme events (e) Daily-scale variability (f) Deviation from Long-Period Average (DLPA) [GIS Maps for monsoon variables].Note: Abbreviation of the name of districts is mentioned in Table 1.


a
Number of Wet Spells
NDB
DHL
JLGN
AMR
NGPR
BD
GD
AKL
WRD
BLD
NSHK
ARG
WSM
YVTM
CHND
THN
JLNA
HNG
GRCH
AHMD
PRB
MUM
BID
NND
RGH
PUNE
LTR
OSM
SLPR
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SNG
KLH
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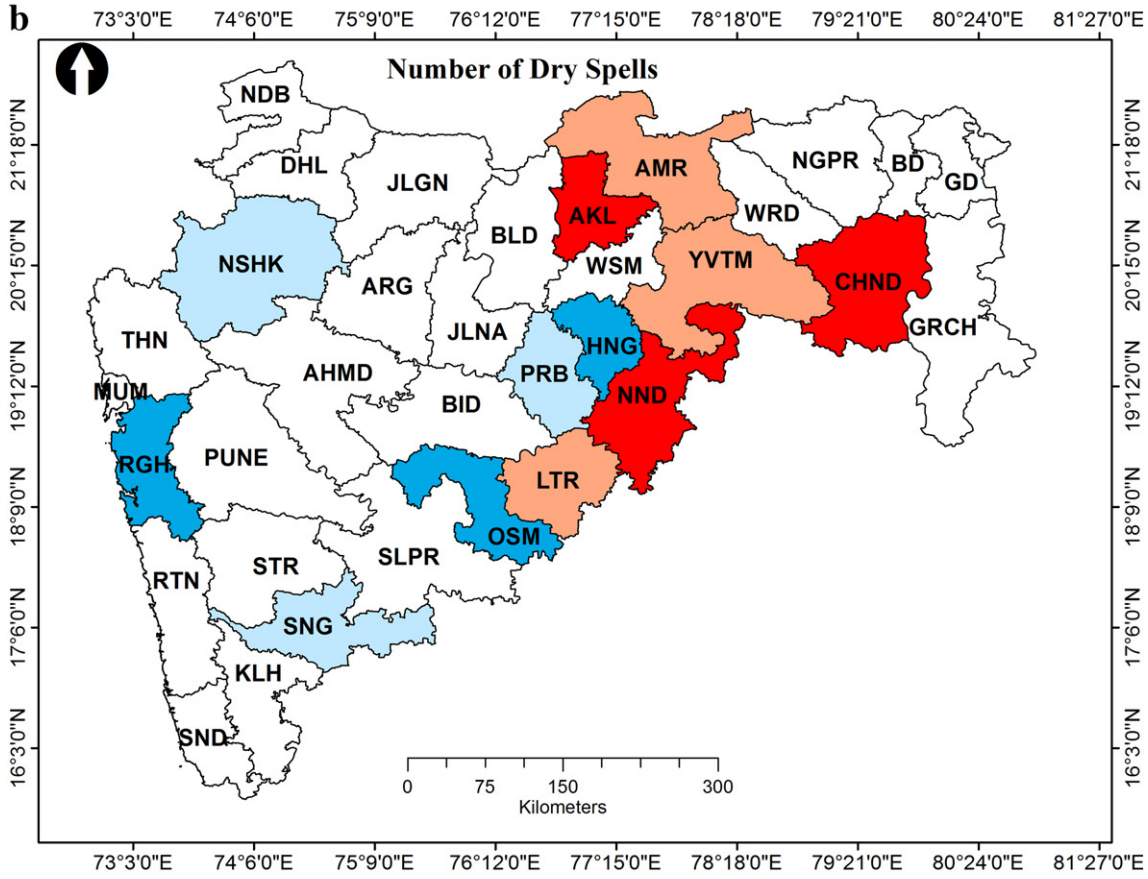
0 75 150 300
Kilometers
73°3'0"E 74°6'0"E 75°9'0"E 76°12'0"E 77°15'0"E 78°18'0"E 79°21'0"E 80°24'0"E 81°27'0"E
21°18'0"N 20°15'0"N 19°12'0"N 18°9'0"N 17°6'0"N 16°3'0"N


b
Number of Dry Spells
NDB
DHL
JLGN
AMR
NGPR
BD
GD
AKL
WRD
BLD
NSHK
ARG
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CHND
THN
JLNA
HNG
GRCH
AHMD
PRB
MUM
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PUNE
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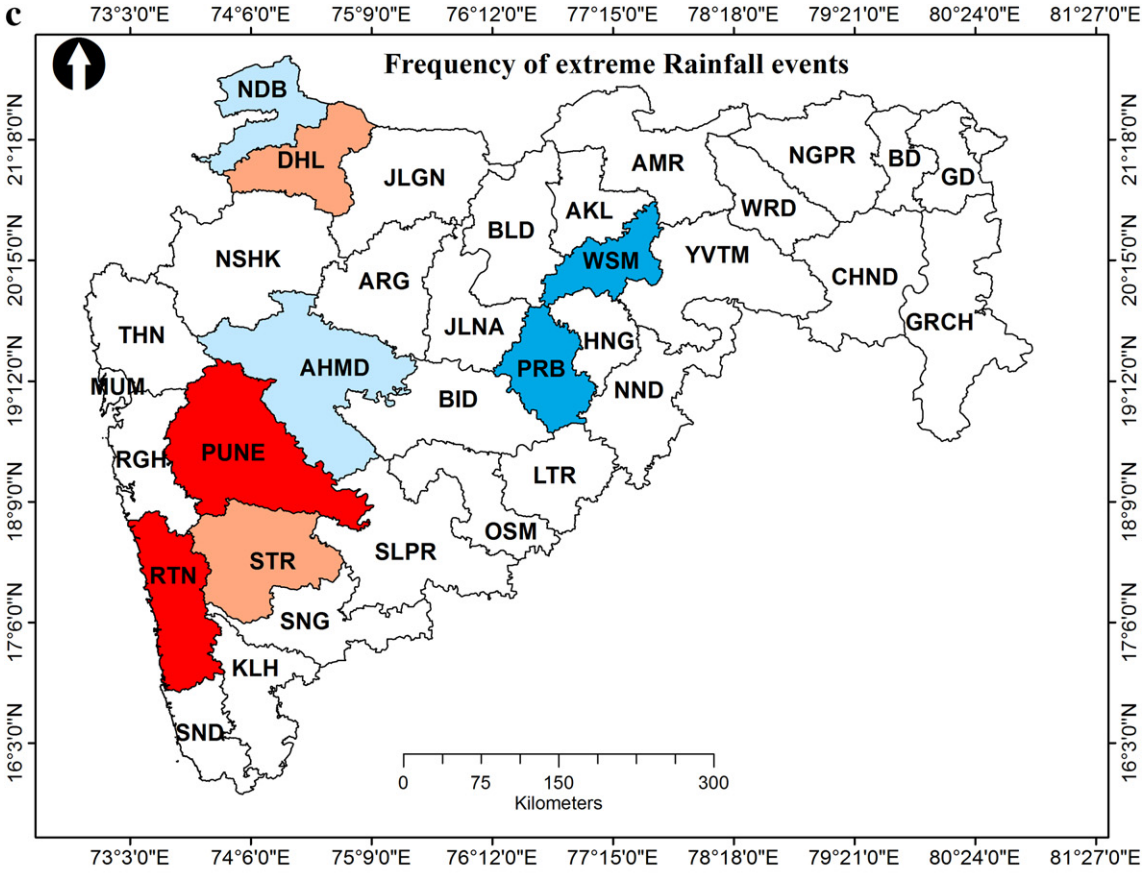

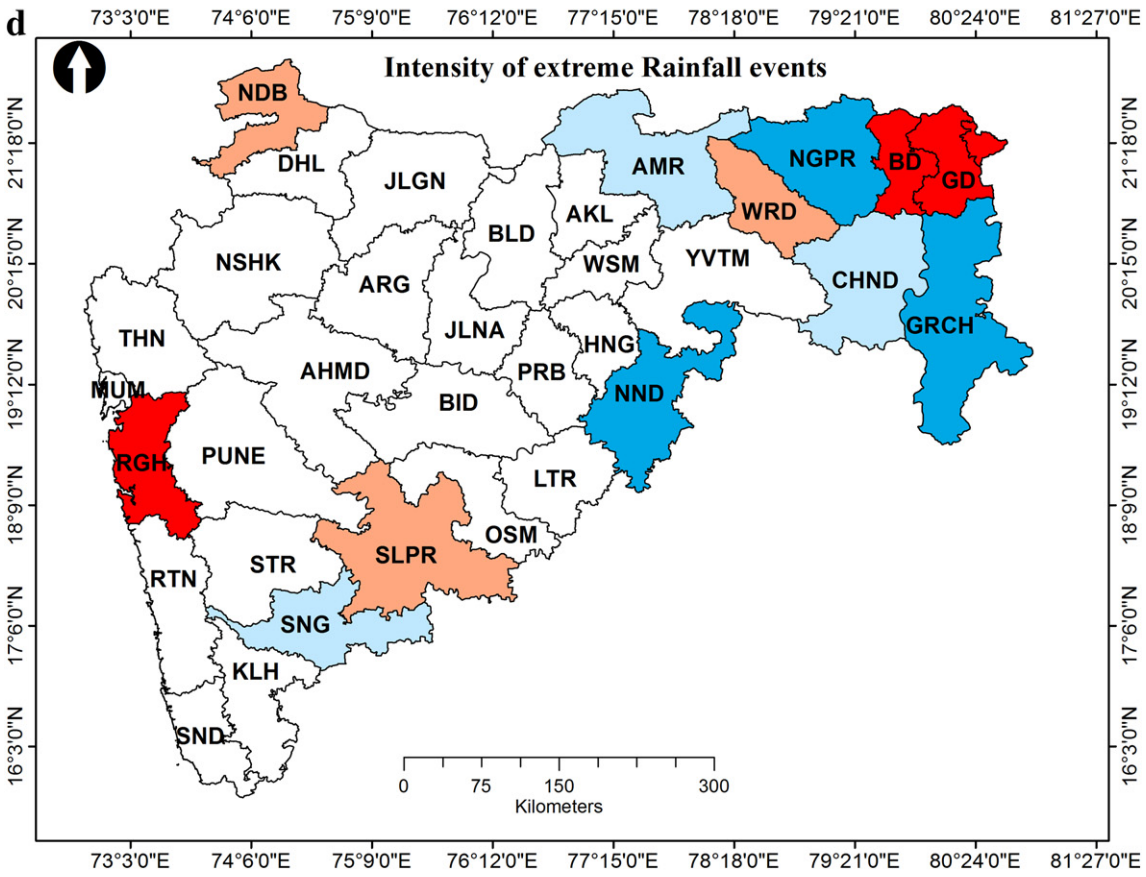

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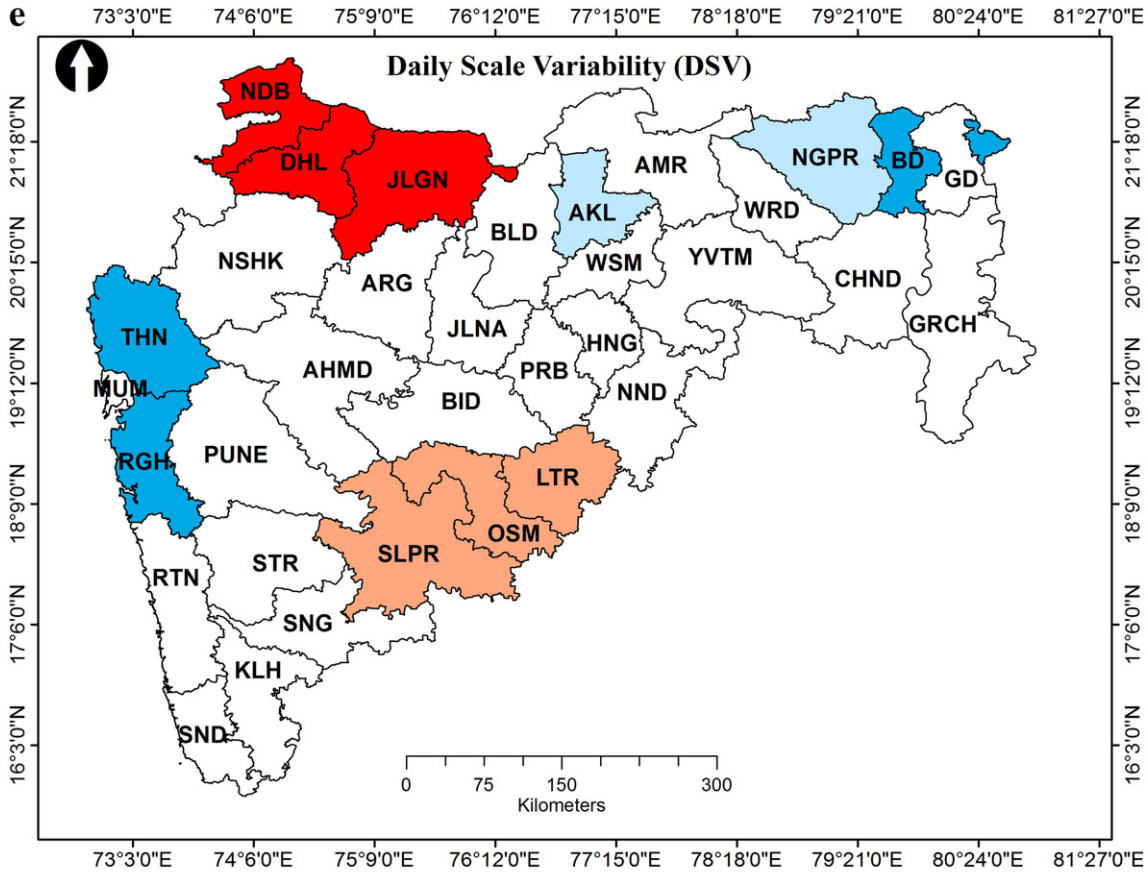

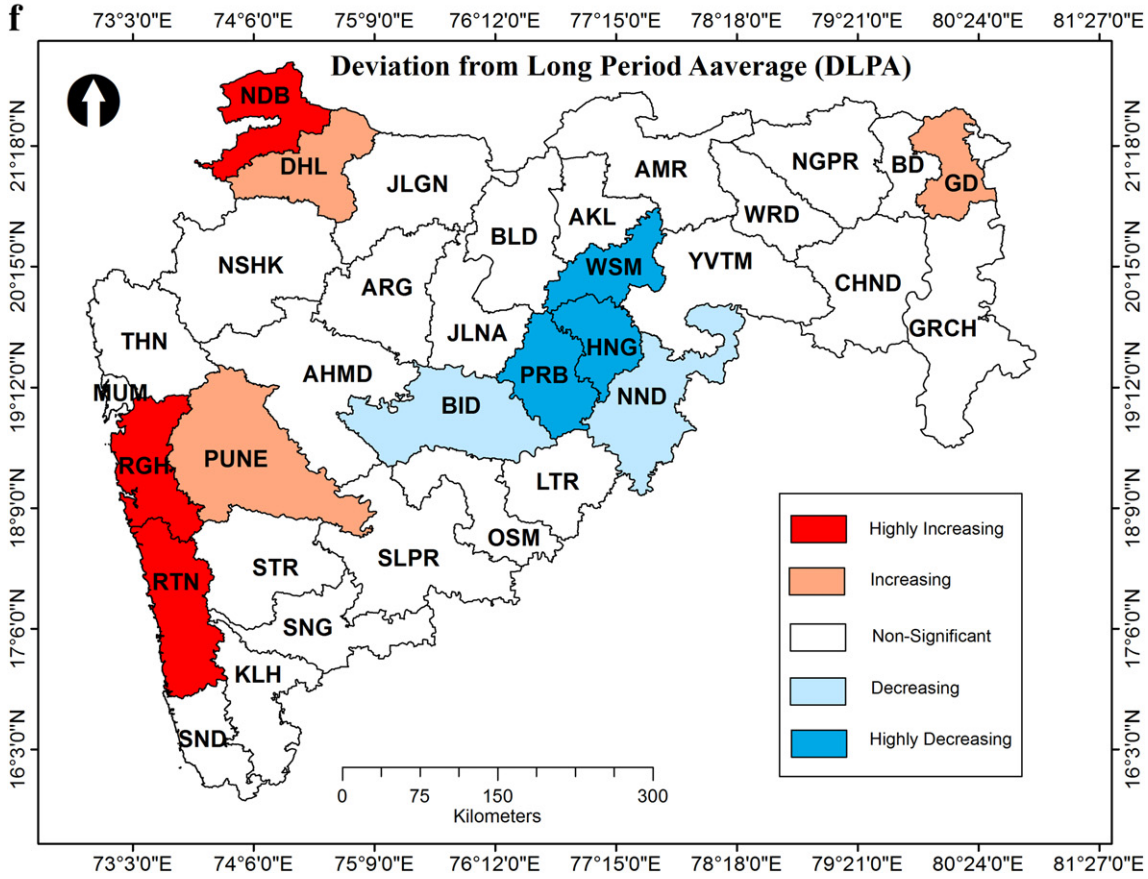

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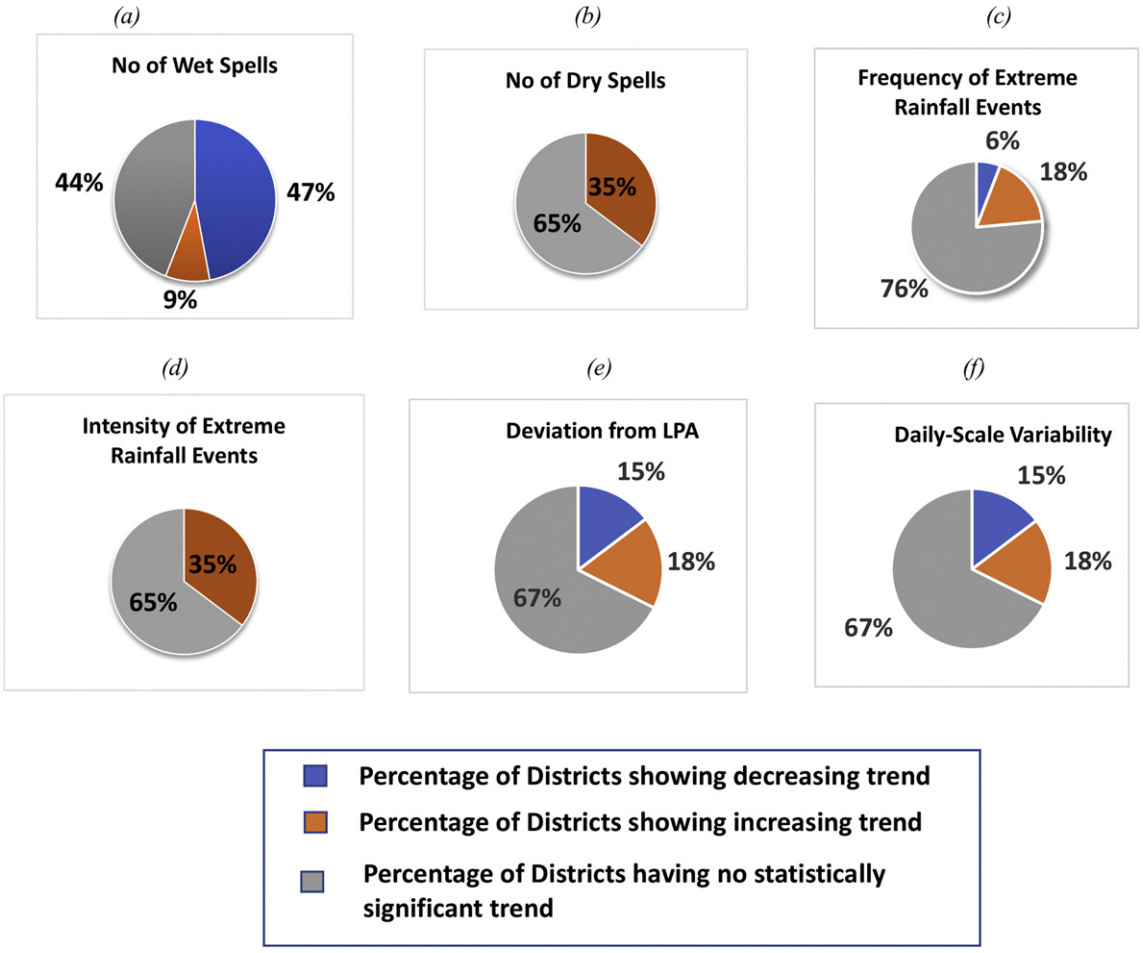


Fig. 4. Examination of trend for monsoon variables over Maharashtra. (a) Number of Wet Spells (b) Number of Dry Spells (c) Frequency of extreme rainfall events (d) Intensity of extreme rainfall events (e) Deviation from LPA (f) Daily-Scale Variability.

During the same year, Maharashtra government acquired the funding of around Rs. 3000 cores from National Disaster Response Force for drought relief which is the highest in comparison to that received by other states in India (*Ministry of Home Affairs, Government of India*, 2016). This clearly shows that Maharashtra Government declared some districts as drought-prone though conditions were not drastic in those districts. It indicates that what the state government declared was "*artificially induced and reported*" drought in these districts, and not meteorological drought.

4.6. Relationship between monsoon variability index (MVI) and agriculture yield

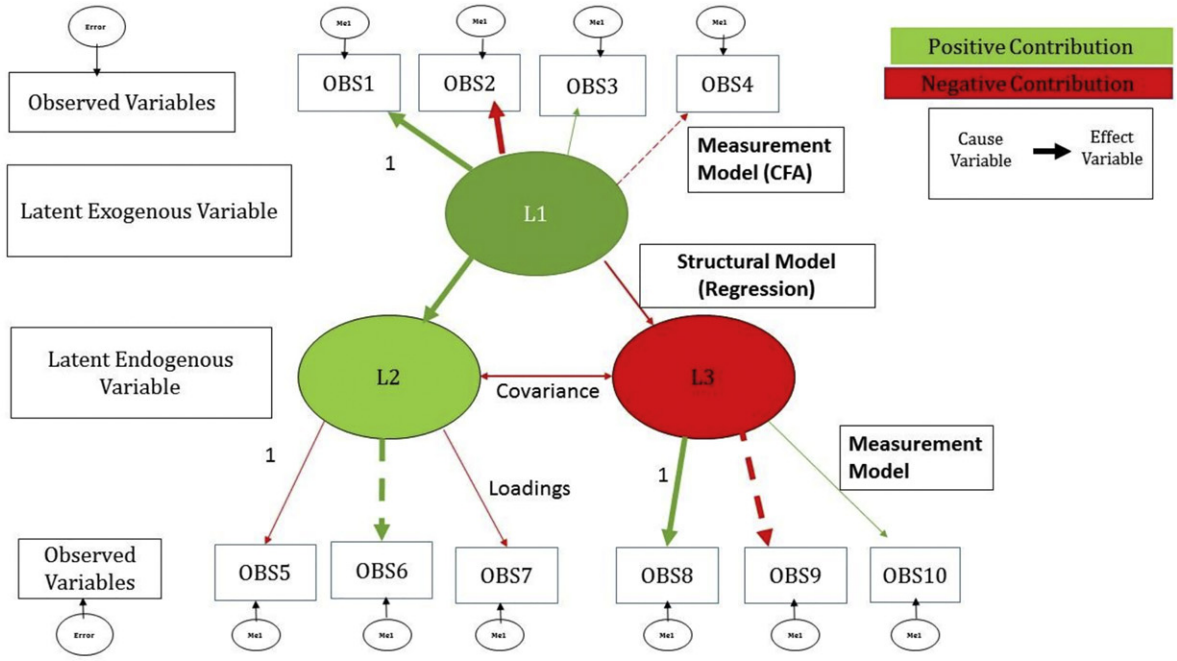
During our analysis of Monsoon variability index (*MVI*), Vidarbha and Marathwada regions were significantly displaying highest Monsoon Variability (*MV*) in comparison to districts in other regions (red and orange color, Fig. 5b). Therefore, we selected one district from each Vidarbha and Marathwada region to establish the link between *MV* and agriculture yield and the cropped area in these districts. Major Kharif crops sown in Maharashtra are sorghum, groundnut, pearl millet, pigeon pea, cotton, and sugarcane. The output of all the monsoon variability parameters i.e. *MVI* was related to average yield and the cropped area along with yield and area of individual crops. The effect due to decrease in agriculture yield has ramification on increasing farmers' vulnerability, specifically in terms of loss of life and poor socio-economic condition. Results for SEM are shown in Fig. 5d and e. In Fig. 5d–e, red and green color represents negative and positive path coefficients (displayed on edges) respectively, and the color intensity is proportional to the magnitude of the effect. The tail of arrow represents cause variable while head of the arrow represents effect variable. Double headed arrows over each variable represent an unexplained part (Fig. 5).

4.6.1. Vidarbha region

Chandrapur was selected for further analysis as it displayed highest *MV*. Increase in *MV* of Chandrapur was manifested by the decrease in frequency, WS, intensity and daily-scale variability (red arrows, Fig. 5d). Monsoon variability is increasing for Chandrapur (Fig. 5b), which leads to significant reduction *in average* yield and cropped area

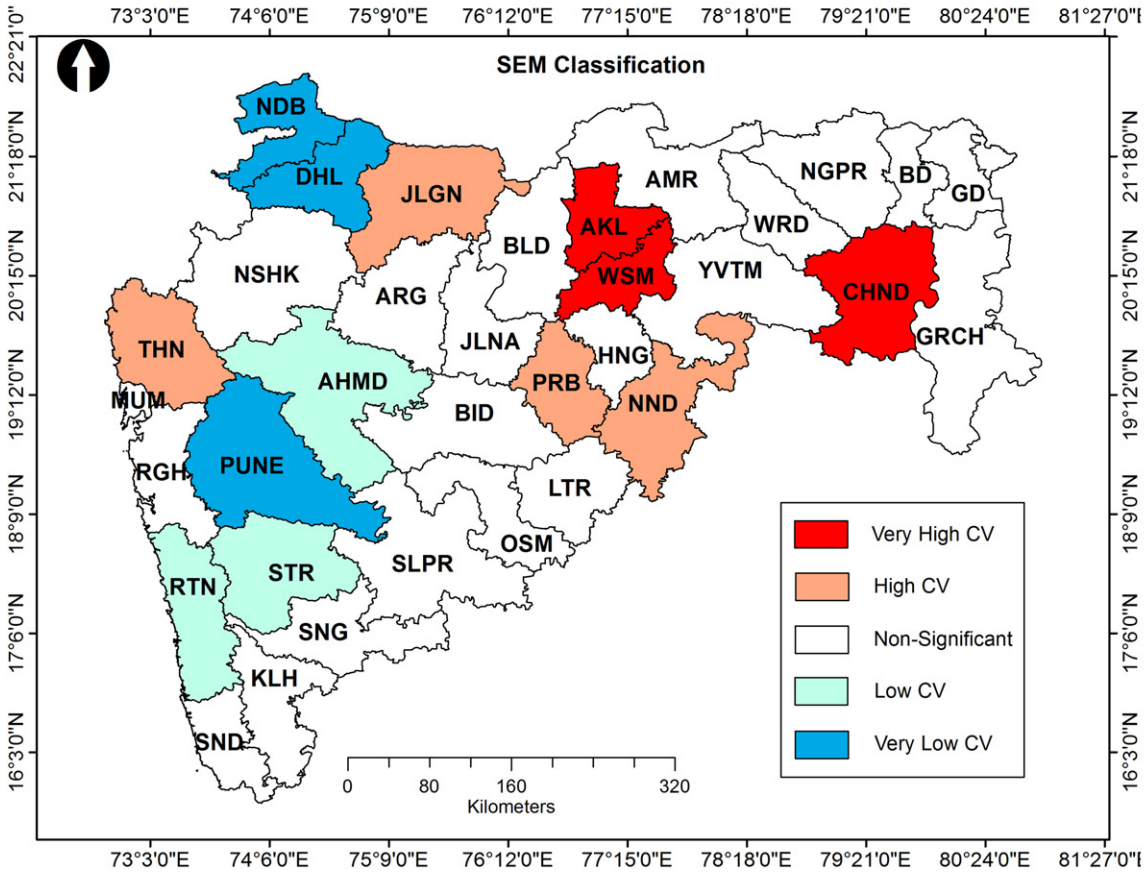
Fig. 5. a. Basic model for Structural equation modeling (SEM).Explanation: SEM used for ranking districts according to monsoon variability. Here monsoon variability (L1) is Latent variable (exogenous variable) which is manifested in terms of other observed variables (OBS1-4 are different monsoon variability parameters such as WS/DS etc.).Latent exogenous variable (Monsoon Variability-L1) is further linked to Latent endogenous variables (Average yield-L2, Total Area-L3, which are manifested in terms of other observed variables (OBS5-7 are yields of different crops and OBS8-10 are cropped area of different crops). Measurement error associated with each exogenous variable is represented by Me_{1-10}.b. Results for monsoon variability index.c. Comparison of DPAP (districts under drought-prone area program) districts by Govt. with current study.d. Structural equation modeling-Model for Chandrapur, Vidarbha (e) Structural equation modeling-Model for Parbhani, Marathwada.Green color indicates positive contribution while red indicates negative contribution.(Coding-DS: Dry Spells, WS: Wet Spells, FREQ: Frequency of extreme rainfall events, INT: Intensity of extreme rainfall events, DSV: Daily Scale Variability; MV: Monsoon Variability; Yield: Average yield, Area: Total area; SRG: Sorghum, GRN: Groundnut, PRL: Pearl millet, PGN: Pigeon pea, CTN: Cotton, SCN: Sugarcane).

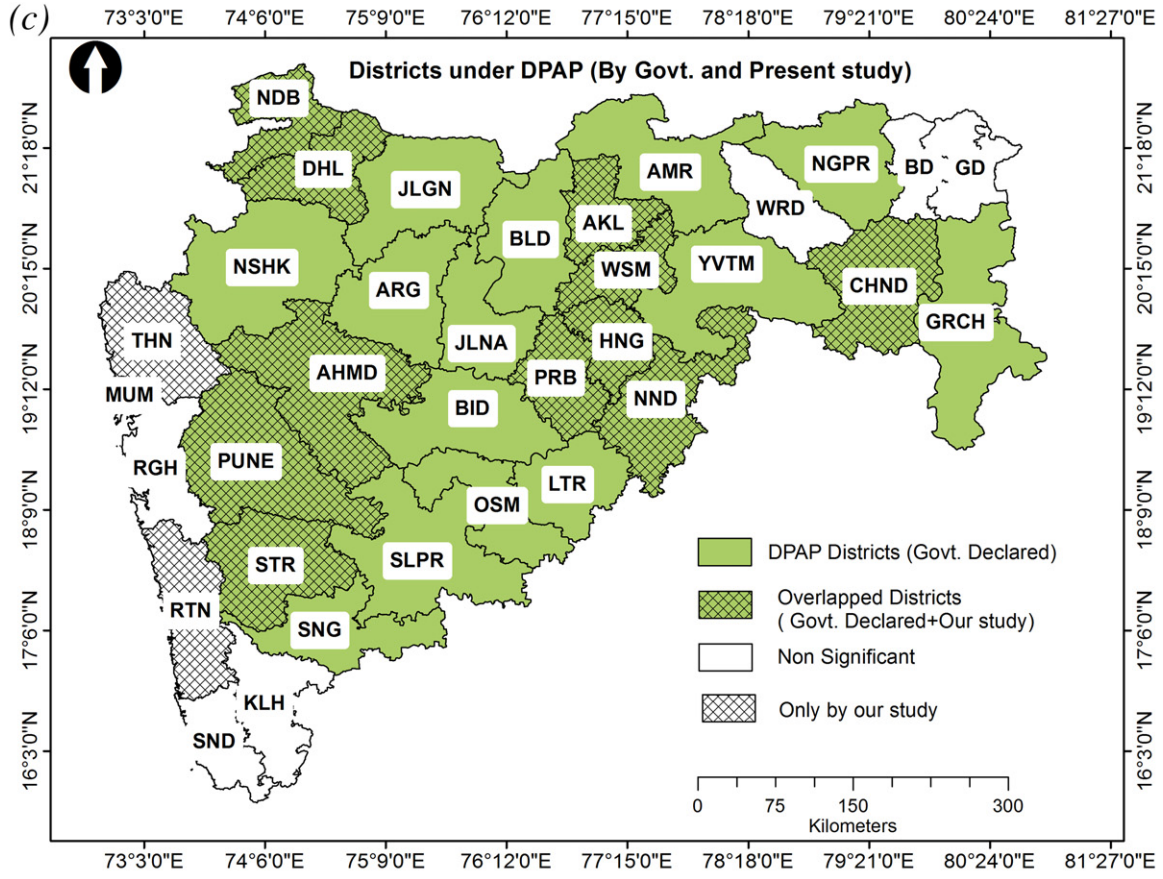
(red arrow from *MV* to yield and area, Fig. 5d). Overall yield showed strong positive effect with groundnut, pearl millet and sugarcane (green color, Fig. 5d). According to this model, yield was decreasing because of increase in *MV*; thereby if the decreasing trend of average yield continues in future then yield of groundnut, sugarcane and sorghum will reduce the most. Further, the decrease in yield of sugarcane,



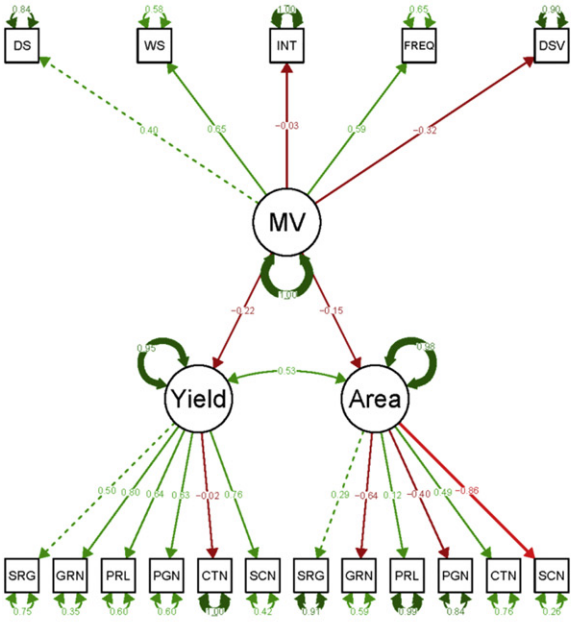
(a) – Basic model for Structural equation modeling (SEM)

(b)

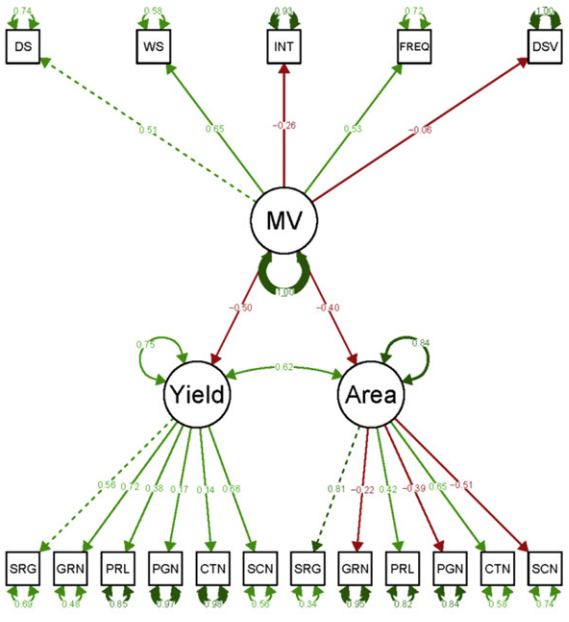




(d) Chandrapur



(e) Parbhani



(d) Structural equation modeling- Model for Chandrapur, Vidarbha (e) Structural equation modeling- Model for Parbhani, Marathwada

Fig. 5 (*continued*).

sorghum, and groundnut was largely contributed by a decrease in WS and frequency of rainfall (Fig. 5d). According to this model, *MV* plays a significant role in reducing the yields of major crops of Chandrapur, therefore, this district should be provided with enough water for improving crop productivity and area. Water supply in form of irrigation or tube wells should be provided to Chandrapur to improve its overall yield. Special attention should be given to weekly forecast monsoon variables especially WS, frequency, and intensity of rainfall, which can help farmers to decide the type of crop to be sown during each season.

The total cropped area was also shown to decrease as a consequence of the increase in *MV*. The total area was negatively related to the area of groundnut, pigeon pea and sugarcane implying that reduction in the total area lead to increase in the area of groundnut, pigeon pea, and sugarcane, leading to failure of these crops as area increased but they might not have sufficient water to grow, thereby, their yield decreased. Crop failure can be the reason for suicides and indebtedness of farmers in Vidarbha region (Basu et al., 2016). According to the model, cotton was not much affected by the increase of *MV*, therefore, as an adaptation measure, farmers should sow cotton in Chandrapur.

4.6.2. Marathwada region

Parbhani displayed highest *MV* among other districts in Marathwada region (Fig. 5b), therefore we identified the relationship between *MV* parameters and agriculture yield of Parbhani. Parbhani displayed an increase in *MV* which was observed in terms of decrease in Wet spells, frequency (strong negative correlation) and intensity. Increase in MV also led to significant reduction in average yield and area (red color, Fig. 5e). Average yield showed strong positive influence on groundnut, sugarcane, and sorghum. According to the model, yield of groundnut, sugarcane, and sorghum reduced the most rather than cotton and pigeon pea.

According to the model increase in *MV* led to a reduction in overall area, which was manifested in terms of increase in the area of groundnut, pigeon pea and sugarcane (red color, Fig. 5e). It shows that cropped area of groundnut, pigeon pea and sugarcane was increasing but their yield was decreasing, which led to crop failure in Parbhani. Increase in the cropped area while the reduction in yield of major crops might have led to the increased socio-economic vulnerability of farmers, which became the main reason for farmers' suicide in this region (Basu et al., 2016). Reduction in yield was mainly due to decline in number of wet spells, frequency, and intensity. It suggests that crops in Parbhani district did not receive enough water but farmers continued sowing more and more such crops, which was the reason for reduction in yield of such crops. For increasing the yield of groundnut and sugarcane, scientists should provide a weekly forecast for parameters of *MV* to avoid adverse effects on agriculture and farmers. As an adaptation measure, farmers of Parbhani should sow cotton and pigeon pea as these crops were not affected much due to increase in *MV*.

4.7. Implications of study for farmers and policymakers

The present study established the link between climate variability with agriculture and farmers' vulnerability which will help in minimizing the economic losses by providing better information regarding cropping pattern for the most vulnerable region. Following the results from different monsoon variability parameters, it was found that districts of Vidarbha and Marathwada region displayed highest monsoon variability post 1976/77 (SI-Table 1). Districts with high variation in terms of WS, DS, intensity, frequency, DLPA and DSV after 1976/77 indicated that these districts are highly affected due to industrialization, urbanization, and regime shift. As per the analysis, Marathwada and Vidarbha regions of Maharashtra are highly sensitive to the changes in climate, for instance, increase in DS/Intensity/DSV and decrease in WS/Frequency/DLPA was at a higher rate for the districts in these regions. High monsoon variability in these regions is also causing increased vulnerability to farmers, agriculturalist, economy, and infrastructure; hence proper planning needs to be done to reduce their vulnerability to monsoon variability. Further, such districts need immediate attention by policymakers in case of occurrence of any hazard. More research is needed to ascertain and quantify the causes for monsoon variability at the district level. Our results indicate that one should not cluster the entire state or region as a single unit before considering the heterogeneity of monsoon variables. The present study also suggests that analysis at the local level for ISM will be more helpful in planning and development of a particular region.

The model also proposes the shift in cropping pattern for the districts showing highest variability in these regions. For example, replacing groundnut, pigeon pea and sugarcane with cotton in Parbhani district of Vidarbha region, and cotton and pigeon pea for Chandrapur district in Marathwada region is one of the adaptation measure proposed in the study. The understanding of the regional level phenomenon is a more structured approach as it helps policymakers and administrative bodies to formulate better policies for farmers. The differences in results of Parbhani and Chandrapur support our argument that policies should be formulated at the district level and India should have District action plan on climate change (DAPCC).

District-action plan on Climate change (DAPCC) proposed during the present work can help in addressing issues having implications not only at regional but also at state and National level. This model can be adopted by any Country, state, and district for agriculture vulnerability assessment and for policy formulation. The model can be replicated at differing administrative units, which suggests its broader implications for a wider audience. The current study also addresses these issues to different stakeholders, government institutions, ministry and agencies that actually make decisions and policies related to climate change and agriculture.

5. Summary and conclusion

Contributing to the growing body of literature on climate variability as referenced in the earlier part of this paper, through a regional scale study, our analysis found decreasing trend for wet spells, frequency of extreme rainfall events and DLPA, while increasing trend was observed for dry spells, intensity of extreme rainfall events and daily scale variability. This study is distinctive in terms of addressing the problem of agriculture vulnerability with reference to monsoon variability and further suggesting adaptation measures at regional and local levels which so far have not been thoroughly investigated. We argue that variability as an aspect of climate change ('*variability in monsoon variability*') needs to be taken more seriously and that it creates unique conditions of vulnerability that necessitates non-generic and location-specific adaptation measures. Our analysis of monsoon variability at regional level signifies spatio-temporal variability and inter and intra zonal heterogeneity in monsoon variability parameters across districts, of Maharashtra, which are demarcated as separate boundaries by government. The exact reason for such incidences should be studied separately by analyzing different atmospheric and meteorological phenomenon. Findings from this analysis highlighted the variation within the districts of the same region which implies that the problems and issues of districts within one region are different and should be addressed separately during policy formulation. Results also suggest that for formulating policies related to climate and agriculture at micro-level, rainfall pattern for each district must be studied individually.

Monsoon variability index indicated that districts under Vidarbha and Marathwada region are at higher risk and need immediate attention from policymakers and scientists. Majority of the agriculture-based decision such as choice of crop, sowing and harvesting time, irrigation requirement is dependent primarily upon monsoon rainfall pattern, thereby, it should be studied in a detailed manner for all the districts.

Impact of increasing monsoon variability on agriculture, farmers, economy and infrastructure warrants immediate attention. Vidarbha and Marathwada region of Maharashtra have least adapted to climate

change, which can be the reason for increasing number of farmers' suicides in these regions (Basu et al., 2016). Findings can be utilized by farmers and policy makers while formulating agricultural policies, risk reduction measures, and adaptation mechanism to address the adverse impacts of climate change. Our study has also identified hot-spots, which needs immediate attention in terms of their infrastructure, planning, agriculture and economic factors.

The present study also specifies which monsoon variability parameters should be given special attention to overcome socio-economic and agricultural vulnerability. It proposes the formulation of district level policy for the benefit of farmers, planning and development, and overall economy of India. This study is an effort to draw the attention of people, farmers, scientists, agriculturalists and the government towards the prevalent scenario in the Maharashtra state. Based on the evidence in our study, we propose a formulation of 'District action plan on Climate change (DAPCC)' so that the situation of each district can be monitored by the experts and the amount of funding can be released accordingly. The study can be further used by government and policy makers to propose adaptation measures by specifically targeting these areas. The study is an attempt to fill the gap in the existing literature by raising local level problems to government and policymakers.

One of the limitations of the current analysis is that the focus is solely on climate factors; however socio-economic factors such as poor selection of crops, and improper utilization of ground-water and stored water, and inefficient methods used for irrigation and poor socio-economic conditions of farmers may also play a role in increasing vulnerability towards drought-like situation. These socio-economic factors should be included in the further analysis of this study.

Future aspects involve applications of results obtained for monsoon variability to assess the sensitivity of agricultural vulnerability at the district level of Maharashtra. Further investigation of crop responses to climate change and monsoon variability should be carried out along with possible adaptation strategies to overcome the risk.

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